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Modeling Sluice Gates in Adaptive Hydraulics (AdH)

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the methodology and implementation of sluice gates into the 2D Shallow Water (SW2D) module of Adaptive Hydraulics (AdH). This technical note also outlines how to incorporate a sluice gate into an AdH-SW2D simulation and presents an example test case. A synopsis of the test case results is discussed.

BACKGROUND: Sluice gates are represented within AdH-SW2D as an internal boundary condition that dictates the head/discharge relationship for the modeled structure. The governing equation for discharge through a sluice gate is given in Equation 1 from Swamee (1992).

$$Q = C_D ab\sqrt{2gh_0} \tag{1}$$

where:

$q =$ Discharge

$C_D =$ Drag Coefficient

$a =$ Sluice Opening Height

$b =$ Sluice Width

$g =$ Gravity

$h_0 =$ Upstream Depth.

Sluice gates can operate under two different discharge scenarios, which are free or submerged flows. Figure 1 from Swamee (1992) illustrates the differences between the two conditions. The definitions for submerged and free flow conditions are given in Equation 2 and Equation 3, respectively, from Swamee (1992).

Submerged Flow Condition

$$h_2 < h_0 < h_{0\max} \tag{2}$$

Free Flow Condition

$h_0 \geq h_{0\max}$

where:

$$h_{0\max} = 0.81a\left(\frac{h_2}{a}\right)^{1.72} \tag{3}$$

$h_2 =$ Downstream Depth

$\mathrm{h}_0 =$ Upstream Depth

$a =$ Sluice Opening Height

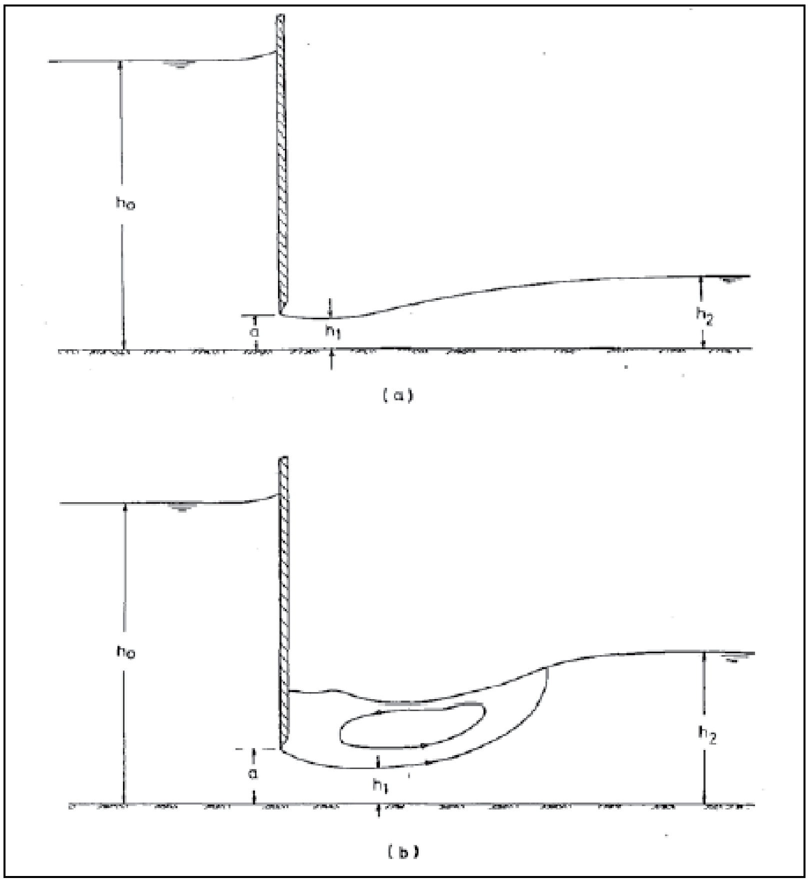

Figure 1. Examples of free (a) and submerged (b) flow (Swamee 1992).

The drag coefficient varies depending on the discharge scenario (either free or submerged). The drag coefficient is generally smaller when in submerged flow but can vary from 0 to approximately 0.6, which is the upper limit for the free flow condition. For the free flow case, the drag coefficient is defined in Equation 4.

$$C_D = 0.611\left(\frac{h_0 - a}{h_0 + 15a}\right)^{0.072} \tag{4}$$

The drag coefficient for the submerged case is defined in Equation 5. As the upstream depth reaches h_{0max}, which is defined above in Equation 2, Equation 5 reduces to Equation 4, which follows the definitions of each case given above.

$$C_D = \frac{0.611\left(\frac{h_0 - a}{h_0 + 15a}\right)^{0.072}\left(h_0 - h_2\right)^{0.7}}{0.32*\left[0.81h_2\left(\frac{h_2}{a}\right)^{0.72} - h_0\right]^{0.7} + \left(h_0 - h_2\right)^{0.7}} \tag{5}$$

Substituting Equation 4 into Equation 1 yields

$$Q = 0.864ab\sqrt{gh_0}\left(\frac{h_0 - a}{h_0 + 15a}\right)^{0.072} \tag{6}$$

Substituting Equation 5 into Equation 1 yields

$$Q = \frac{0.864ab\sqrt{gh_0}\left(\frac{h_0 - a}{h_0 + 15a}\right)^{0.072}\left(h_0 - h_2\right)^{0.7}}{0.32\left[0.81h_2\left(\frac{h_2}{a}\right)^{0.72} - h_0\right]^{0.7} + \left(h_0 - h_2\right)^{0.7}} \tag{7}$$

Equation 6 and Equation 7 are used within AdH-SW2D to calculate the discharge through the sluice gate for the free and submerged conditions, respectively.

Typically, when modeling a sluice gate within AdH-SW2D, an operational schedule will be established for the structure in question from historical data or typical operating procedures. AdH-SW2D should not be used to establish an operational schedule for a proposed structure as a physical model would be more appropriate. This is due to AdH-SW2D applying the downstream flow over the entire length of the sluice gate. In reality, there would be a reduction in the effective length, or a flow shadow, on the downstream flow. This phenomena is typically quantified by using a physical model to estimate a coefficient of contraction, which is why a physical model is more appropriate for establishing operational schedules (USACE 1987). However, AdH-SW2D can estimate the behavior of flow around a sluice gate with an established schedule. Typically, the operational schedule will be created to maintain a desired upstream head. For the purposes of this test case, an upstream head of approximately 7 meters (m) is maintained with the variable inflows. This operational schedule will be incorporated into the AdH-SW2D boundary conditions (BC) file, which is described in the next section. In view of the limitations listed above, operational decisions should not be made based on the sluice gate implementation within AdH-SW2D.

TEST CASE FORCING: The test case was forced with the following arrangement:

1. The volumetric flow was stair stepped from 45 to 60 to 90 to 150 cubic meters per second (cms).
2. A constant tailwater of 1 m was held at the outflow boundary.
3. The upstream reference node string was extended for stability purposes. (See McKnight et al. [2018] for a detailed description of the reasoning for this.)
4. The bottom elevation is constant.
5. See Figure 2 for locations of strings.

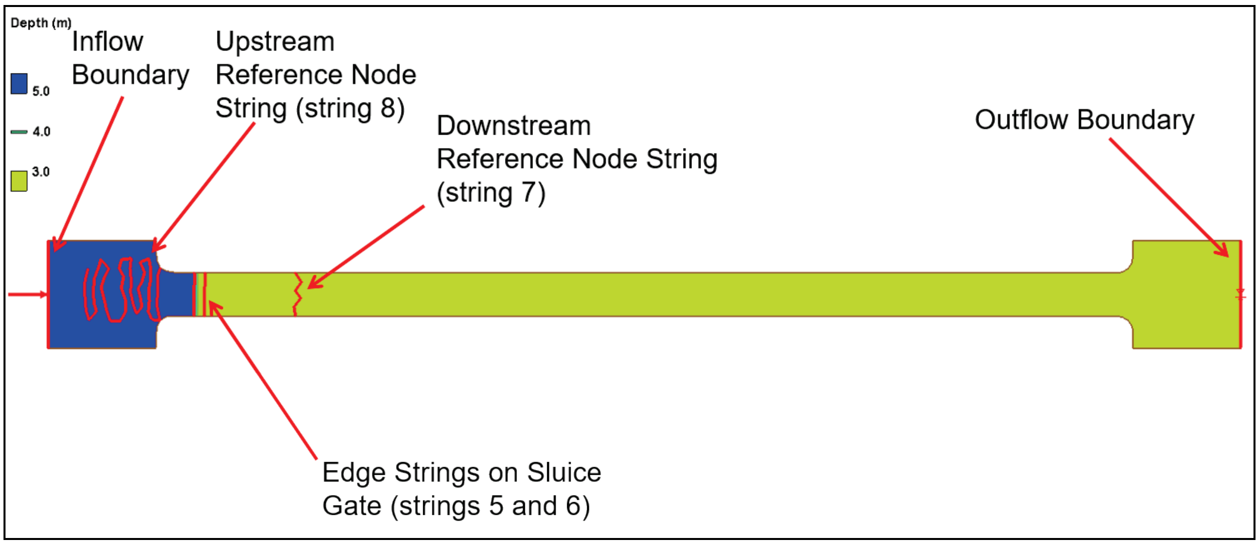

Figure 2. Locations of boundary and reference strings for test case (plan view).

IMPLEMENTATION: The parameters are input into AdH-SW2D using control cards in the BC file. A description of the inputs that are entered into the BC file are shown below in Figure 3.

Figure 4 shows how to enter the sluice gate parameters into the AdH-SW2D BC file. This is an example from the test case that will be presented in this paper.

SLUICE

NUMBER OF SLUICE GATES

Field	Type	Value	Description
1	char	SLUICE	Card type
2	int	≥ 1	Number of weirs

SLS

SLUICE GATE PARAMETERS

Field	Type	Value	Description
1	char	SLS	Card type
2	int	≥ 1	Sluice Gate Number
3	int	≥ 1	String upstream of sluice gate (node)
4	int	≥ 1	String downstream of sluice gate (node)
5	int	≥ 1	Sluice string on upstream (edge)
6	int	≥ 1	Sluice string on downstream (edge)
7	real	≥ 0	Length of sluice gate (*b* in the previous equations)
8	int	≥ 1	Time series defining the sluice gate opening over time (*a* in the previous equations)

Figure 3. Description of sluice gate card (Berger et al. 2017).

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Sluice Gate Parameters
SLUICE 1
SLS 1 8 7 6 5 40 5
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Figure 4. Example of sluice gate card from test case BC file.

The major points to highlight are the following:

1. The upstream reference node string is labeled as 8 in the third entry (SLS is considered entry 1, and the downstream reference node string is labeled as 7 in the fourth entry. These node strings are used to calculate the head difference across the structure. See Figure 2 for the locations of these strings within the model.
2. The upstream edge string on the sluice gate is labeled as 6 in the fifth entry, and the downstream edge string is labeled as 5 in the sixth entry. See Figure 2 for the locations of these strings in the mesh.
3. The length of the sluice gate (across channel) is in the seventh entry and is set to 40 m. (Note that this does not have to match the actual length in the mesh as this value is only used to calculate the volumetric flowrate to be output on the downstream sluice edge string.)

4. The value in the final entry references the XY time series (5) number that dictates the sluice gate opening schedule. See Figure 5 for an example of the time series.
5. The elements between the two edge strings on the structure must be set to a different material, and the BC file must have an OFF card that removes that material from the hydraulic calculations. (If the material is 2, then the off card would read OFF 2.)
6. More than one element must be located across the structure in between the two edge strings. (See McKnight et al. 2018 for a detailed description.)

Figures 5 and 6 detail how to include the gate schedule as a time series of the sluice gate opening heights. An inflow boundary time series of volumetric flowrates has been created to correspond to this gate opening time series. All changes in height are ramped over 0.1 hour for this test case. Note that the number 5 refers to the series ID, which is incorporated into the final column of the SLS card detailed in Figure 4.

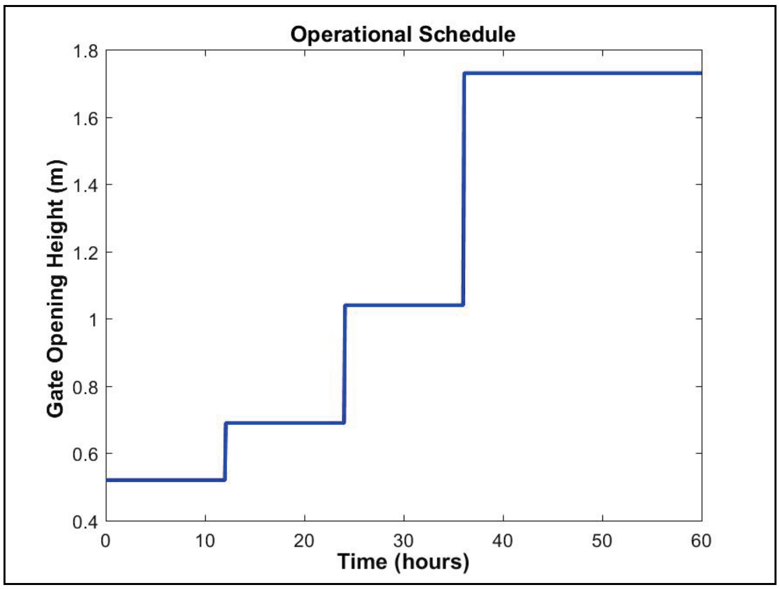

Figure 5. Gate opening schedule.

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Time Series for Sluice Opening
XY1 5 8 2 0
0.0  0.52
12.0      0.52
12.1      0.69
24.0      0.69
24.1      1.04
36.0      1.04
36.1      1.73
60.0      1.73
```

Figure 6. Time series for gate opening schedule (hours and meters).

TEST CASE RESULTS: Figure 7 displays the volumetric flow rate through the sluice gate for the entirety of the test case simulation. The model reaches steady state for every change in flow rate and opening height. There are small instabilities associated with the ramping of the flows and gate openings, but the model converges to steady state quickly after ramping. The model applies the theoretical steady state discharge equations for every flow rate.

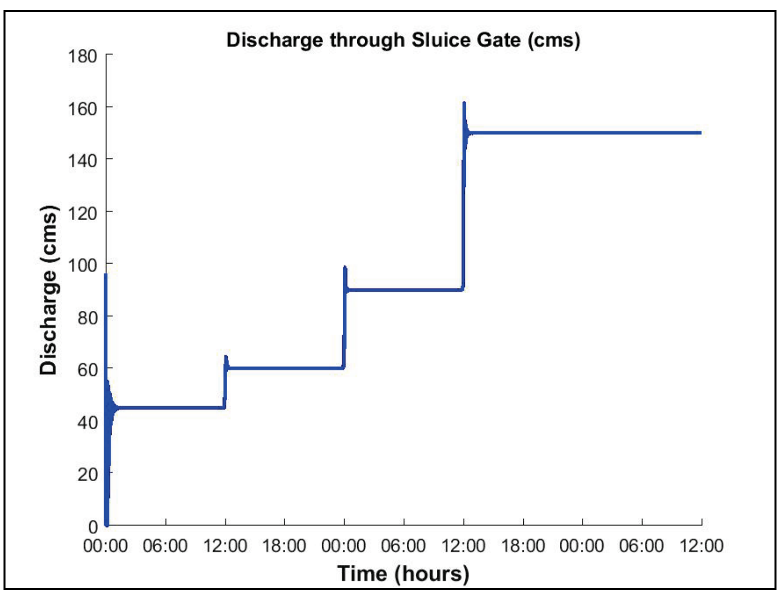

Figure 7. Discharge through sluice gate for test case.

SUMMARY OF FINDINGS: AdH-SW2D is capable of accurately calculating the flow behavior around sluice gates. Sluice gates are sensitive to changes in volumetric flow rates and changes in the gate opening heights. Choosing an appropriate time-step and arranging the reference strings in a reasonable and appropriate manner are paramount to obtaining appropriate simulation results. Refer to McKnight et al. (2018) for a detailed discussion of estimating time steps and arranging reference node strings.

ADDITIONAL INFORMATION: For additional information, contact Jared McKnight, Research General Engineer, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180 at 601-634-2844; email: *Charles.J.McKnight@erdc.dren.mil*. This effort was funded through the 219 Office of Research and Technology Transfer (ORTT) Initiatives Technology Transition Advancement Program.

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